Theory Outlook

(disclaimer: personal)

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Neutrino 2020, Fermilab & all over the world

Neutrino mass special

only failure of SM

(the) window into new physics

touches into the core of it all

we have come a long way

neutrino mass and lepton mixing matrix being untangled

a long way to go

to get there = a self-contained theory of neutrino mass

not models for neutrino mass

analogy:

- neutral currents in the SM
- Higgs origin of SM particle masses

examples

SO(10) GUT

Fritsch, Minkowski '74

Georgi '74

$$\Psi_{16} = \begin{pmatrix} u \\ u \\ u \\ \nu \\ d \\ d \\ d \\ e \\ e^c \\ d^c \\ d^c \\ d^c \\ \nu^c \\ u^c \\ u^c \\ u^c \end{pmatrix}$$

Generation unified → (heavy) RH neutrino

↓

small neutrino mass

Beautiful, but not self-contained,
hard to make predictions

$$\Lambda_{strong} = \frac{M_P}{\sqrt{N}} \quad (\mathrm{N} \sim 100\text{'s}) \quad < 10^{17}\, GeV$$

Dvali '2007

$$\Lambda_{strong} \gg M_{GUT} \gtrsim 10^{16}\, GeV$$

proton stability

no room?

Minimal Supersymmetric Standard Model

particle - sparticle

↓

Zino (partner of Z) - role of RH neutrino

↓

neutrino mass through a
small vev of sneutrino

too many parameters, not self-contained
- fix the parameter space!?

Left-Right Symmetric Theory

Mohapatra, Pati, Salam, GS '74-'79

parity violation - spontaneous origin

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad | \quad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

↓

neutrino mass related to parity violation

Minkowski '77

Mohapatra, GS '79 '81

some forty years later:

Nemevsek, Tello, GS 2012

self-contained, predictive
theory of neutrino mass

Tello, GS 2016-2020

Does gravity matter?

Planck scale suppression?

situation more subtle

Dvali, Folkerts, Franca 2013

gravitational anomaly

Dvali, Funcke 2016

↓

additional ~ Higgs effect → $\langle \bar{\nu}_R \nu_L \rangle = \Lambda^3_{gravity}$ SU(2) doublet

(analog of QCD condensate)

can affect neutrino mass

back up slides

The core of it all

Neutrino = anti neutrino?

Majorana '37

⬇ Majorana mass

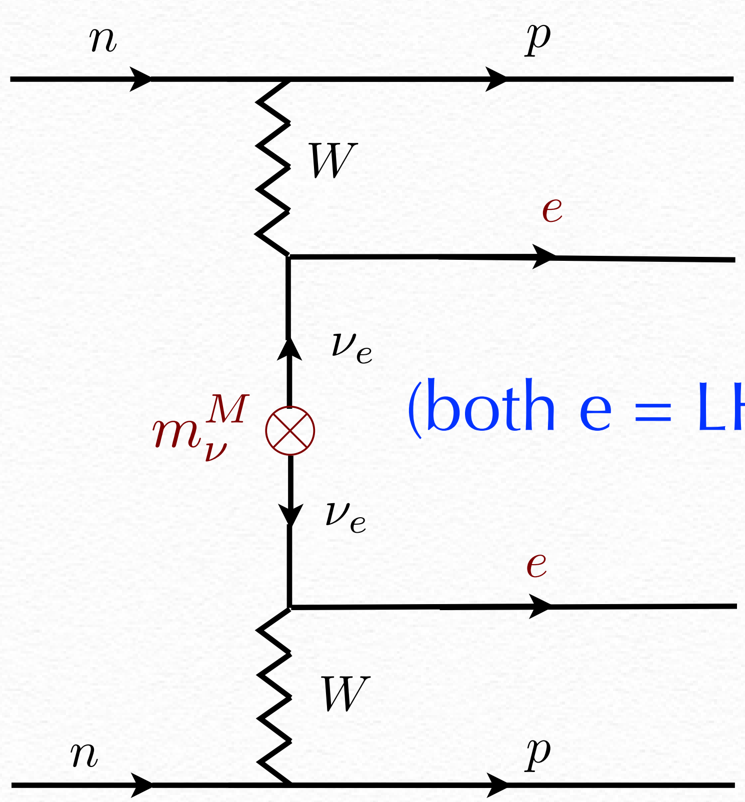
Lepton Number Violation (LNV)

- neutrinoless double beta decay *Furry '38*

- LNV@hadron colliders: KS process *Keung, GS '83*

Neutrinoless double beta decay

talks by Detwiller, Gomez Cadenas, Grant, Heise, Kermaidic, Menendez, O'Donnel, Petcov



(both e = LH)

$$\mathcal{A}_\nu \propto \frac{G_F^2 m_\nu^{ee}}{p^2} \quad (p \simeq 100\, MeV)$$

$$m_\nu^{ee} \lesssim 0.1 eV$$

GERDA 2020

probe of neutrino Majorana mass?

Caveat - new physics?

Feinberg, Goldhaber '59
Pontecorvo '64

d = 9 operator $\dfrac{1}{\Lambda_{\not L}^5}(e\,e\,u\,u\,\bar{d}\,\bar{d})$

$$\mathcal{A}_{NP} = \Lambda_{\not L}^{-5} \lesssim 10^{-18}\, GeV^{-5}$$

compare → $\Lambda_{\not L} \gtrsim TeV$

LHC?

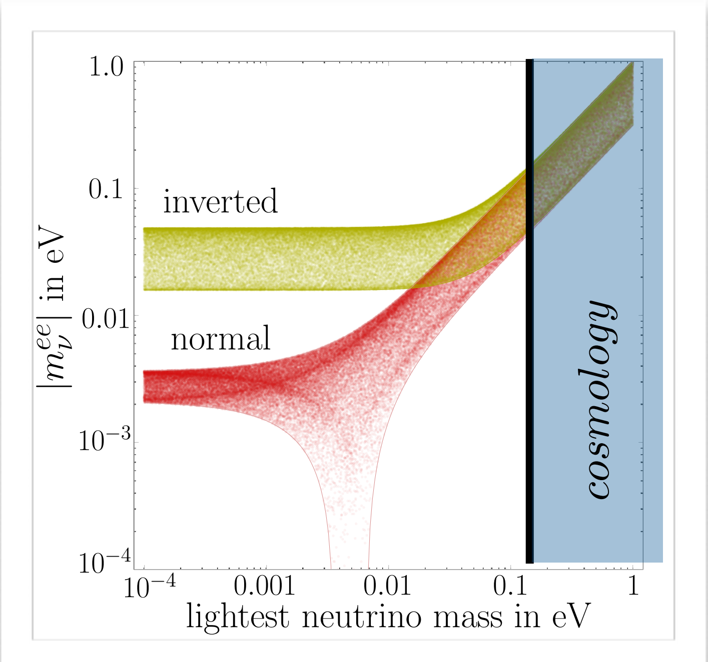
$$\mathcal{A}_{\nu} \propto \frac{G_F^2 m_\nu^{ee}}{p^2} \lesssim G_F^2\, 10^{-8}\, GeV^{-1}$$

Neutrino vs new physics

measure electron polarisation

- e = RH → eureka: new physics
- both e = LH → new physics, not neutrino?

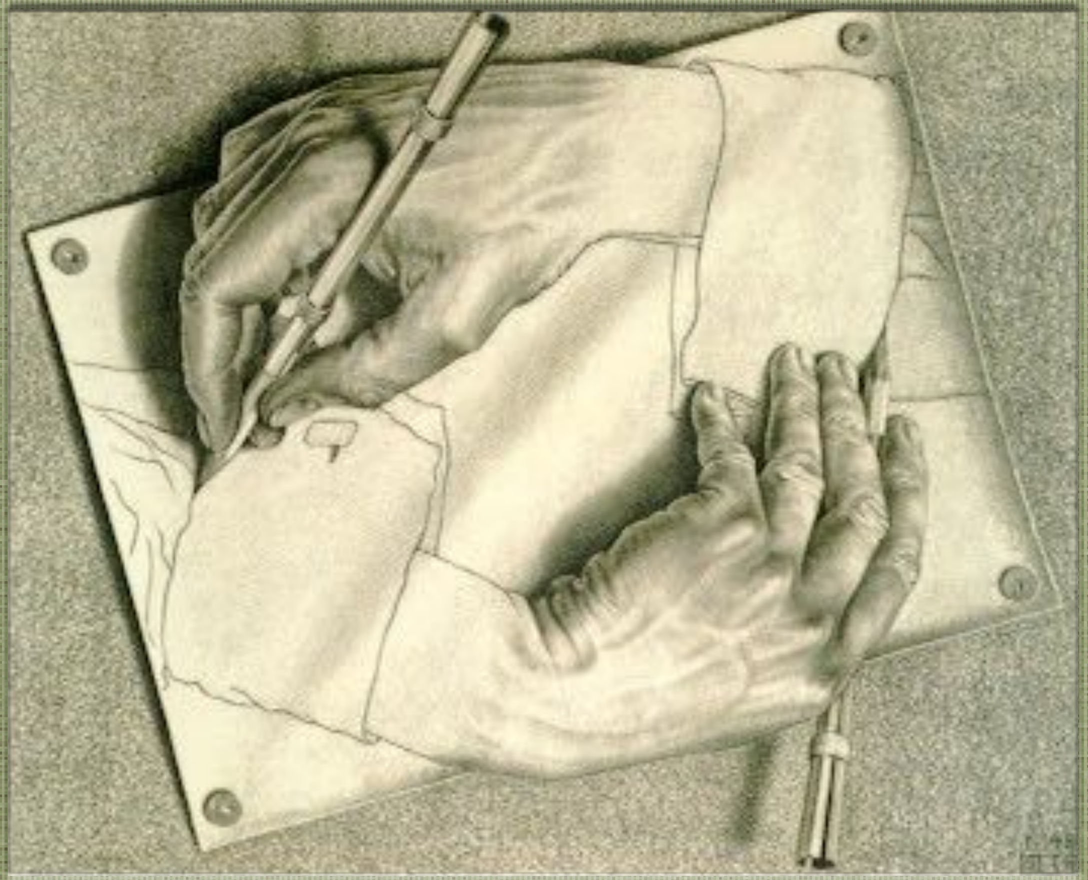
back up slides



normal hierarchy?

probe of the theory of neutrino mass?

The nature and origin of neutrino mass



Back to Basics: LR symmetry

Parity violation

Lee, Yang '56

experiment: maximal

↓

$$J_\mu^W = \bar{u}_L \gamma_\mu d_L + \bar{\nu}_L \gamma_\mu e_L$$

V - A theory

Marshak, Sudarshan '57

conjecture:
L-R symmetry hidden

Lee, Yang '56

right and the left. If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry. If this

Standard Model

Glashow '61

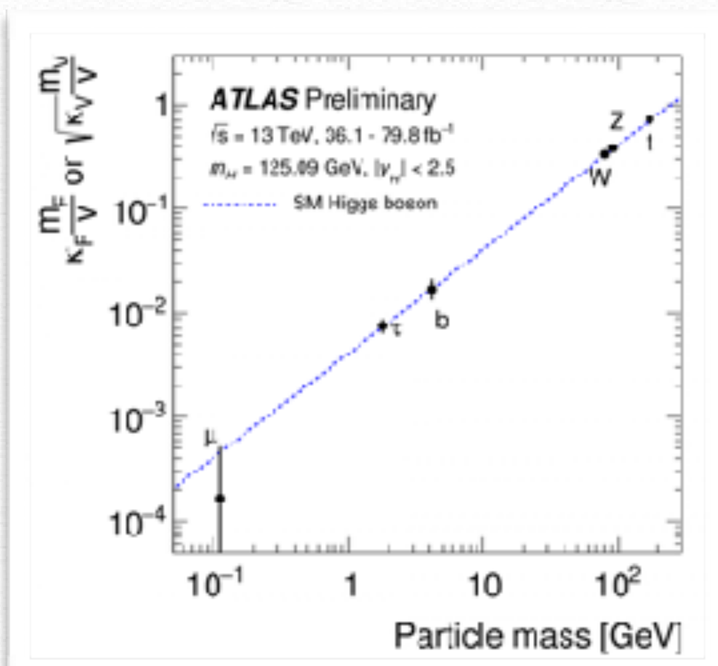
Maximal parity violation crucial

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R \quad d_R$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R$$

→ Higgs doublet *Weinberg '67*

Higgs decays predicted



"V-A was the key" *Weinberg 2009*

↓

Theory of the origin of mass

Neutrino mass failure

structure + minimality

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \Big| \quad e_R$$

↓

neutrino = massless

Imagine parity conserved

Lee, Yang = wrong

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \overline{q_L} M q_R \qquad \begin{pmatrix} u_R \\ d_R \end{pmatrix} = q_R$$

direct mass terms

$$M_u = M_d$$

split: needs adjoint (real triplet) T

$$\mathcal{L}_Y = \overline{q_L}(M + Y_T T) q_R \qquad \langle T \rangle = v \, \mathrm{diag}(1, -1)$$

$M_Z = 0$ → needs more Higgs   predictions gone

P conserved: a curse …

…a blessing, too

vector-like world → neutrino massive

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

conflicting situation

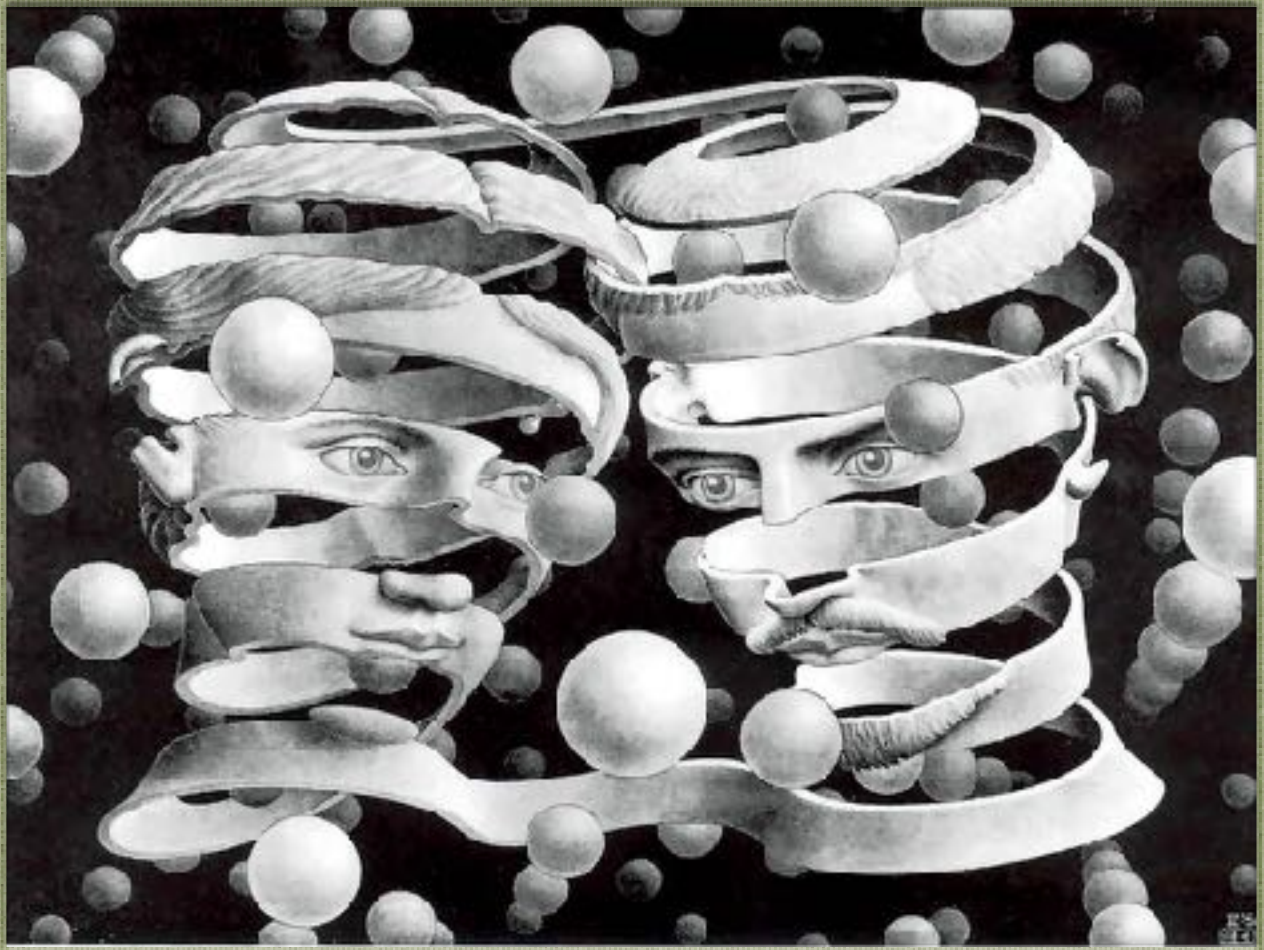
Charged fermions: no LR symmetry

Neutrino: LR symmetry

↓

break parity (LR) spontaneously

The theory



Left-Right Symmetric Model

Mohapatra, Pati, Salam, GS '74-'75

$$W_L \quad \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \Big| \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix} \quad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \quad W_R$$

$$M_{W_R} \gg M_{W_L}$$

seesaw $$m_\nu = m_D \frac{1}{M_N} m_D \quad \leftarrow \quad M_N \propto M_{W_R} \qquad N \equiv \nu_R^*$$

↓

neutrino light ~ parity broken strongly

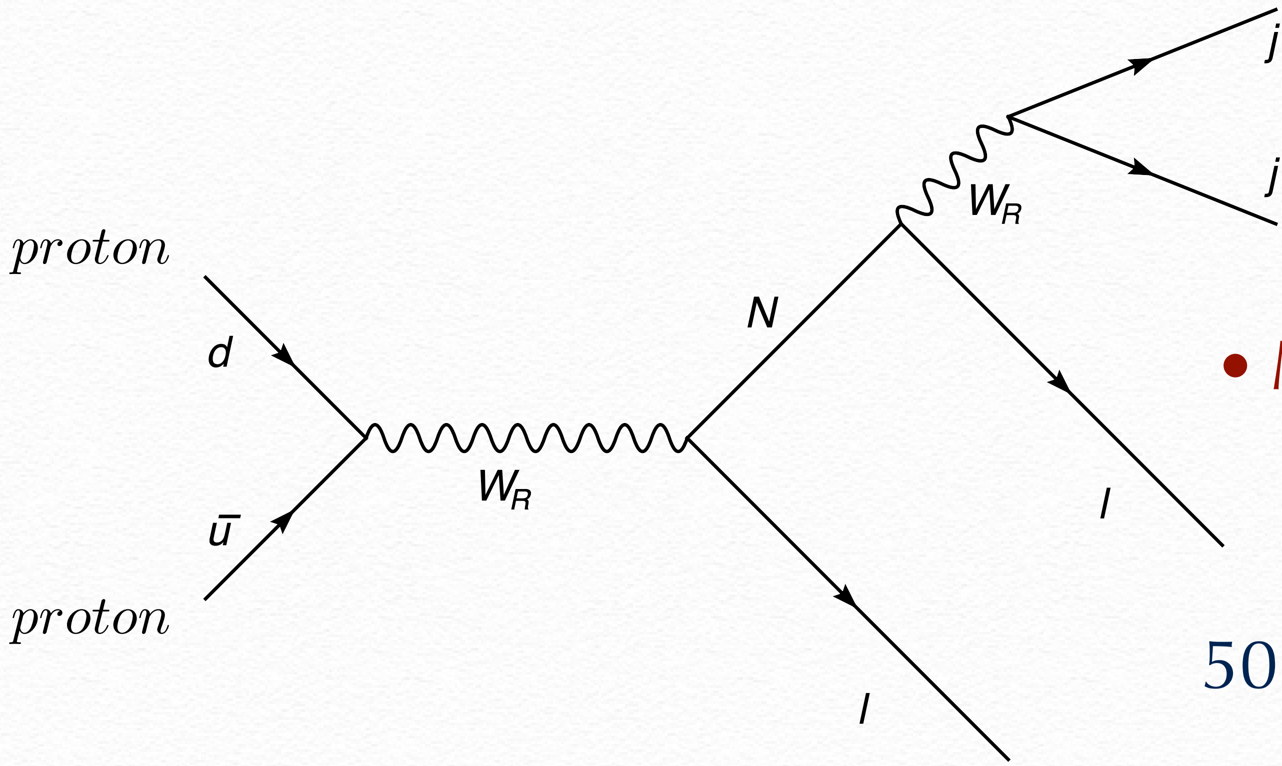
SM: $M_{W_R} \to \infty$

Minkowski; Mohapatra, GS;
Glashow; Gell-Mann et. al.; Yanagida

From Majorana to LHC

Keung, GS '83

direct LNV@hadron colliders: KS process



- Majorana nature of N

50% lepton
50 % anti-lepton

- connection with $0\nu2\beta$

Ferrari et. al. 2000

- connection with LFV

Maiezza, Nemevsek, Nesti, Popara, Tello, Vasquez, Zhang, GS 2010-2019

Tello PhD thesis 2012

Dev, Mohapatra, Zhang 2013-2019

Self-contained theory

Nemevsek, GS, Tello 2012

GS, Tello 2016, 2018, 2019

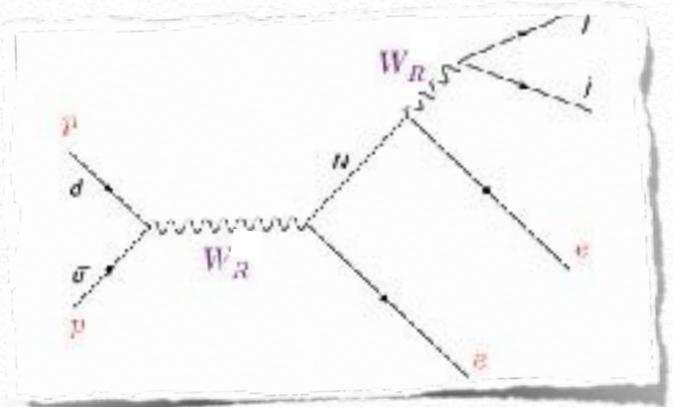
$$\Gamma(N \to We) \propto \frac{m_N^2}{M_W^2} m_\nu$$

LR for neutrino

analogy

$$\Gamma(h \to \bar{f}f) \propto \frac{m_f^2}{M_W^2} m_h$$

SM for charged fermions

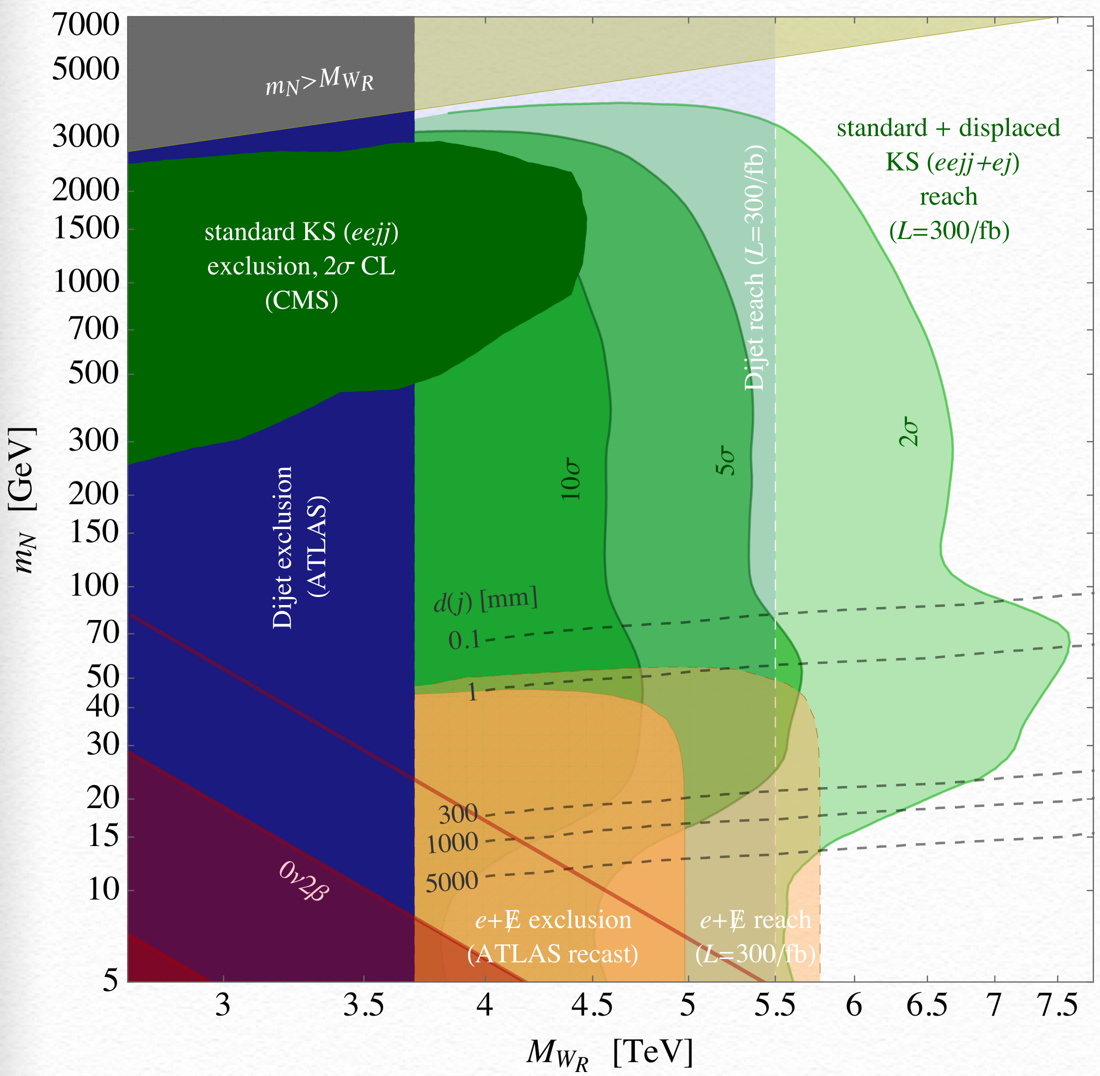


$M_{W_R} \gtrsim 4 - 5\,TeV$ depends on m_N

ATLAS 2019

neutrinos (N_R). A search for W_R boson and N_R neutrino production in a final state containing two charged leptons and two jets ($\ell\ell jj$) with $\ell = e, \mu$ is presented here. The exact process of interest is the Keung–Senjanović (KS) process [10], shown in Figure 1. When the W_R boson is heavier than

Nemevsek, Nesti, Popara 2018

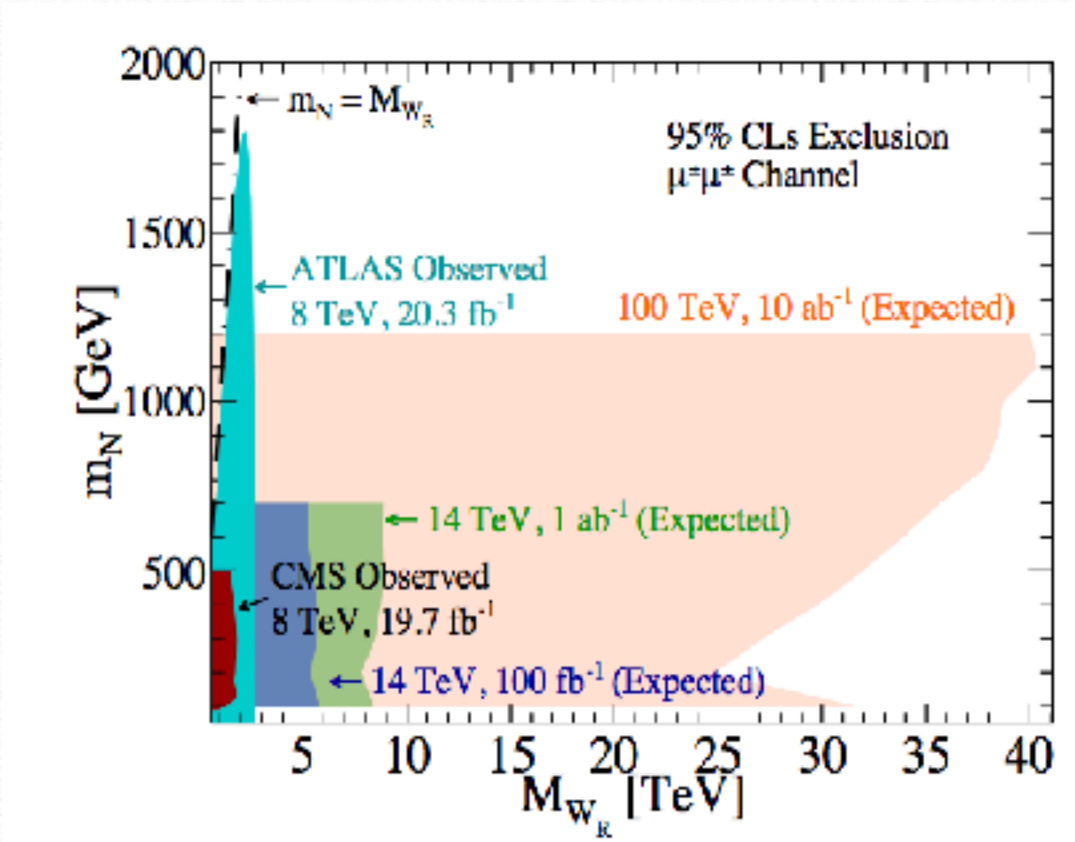


LHC reach

$M_{W_R} \gtrsim 4\,TeV$ dijets ATLAS 2019

100 TeV collider reach

Ruiz 2017



Summary

- sensitive to high scales, even gravity — blessing&curse
- few genuine theories, LR unique ~ SM — self-contained, predictive
- neutrinoless double beta decay crucial — towards Majorana

  ⬇ ?

- LNV at hadron colliders equally important — probe of Majorana nature of RH neutrino
- all about LR symmetry — as is the very essence of the SM

Weinberg:

"V-A was the key"

" Will V+A be the key?"

Thank you

Effective operator analysis

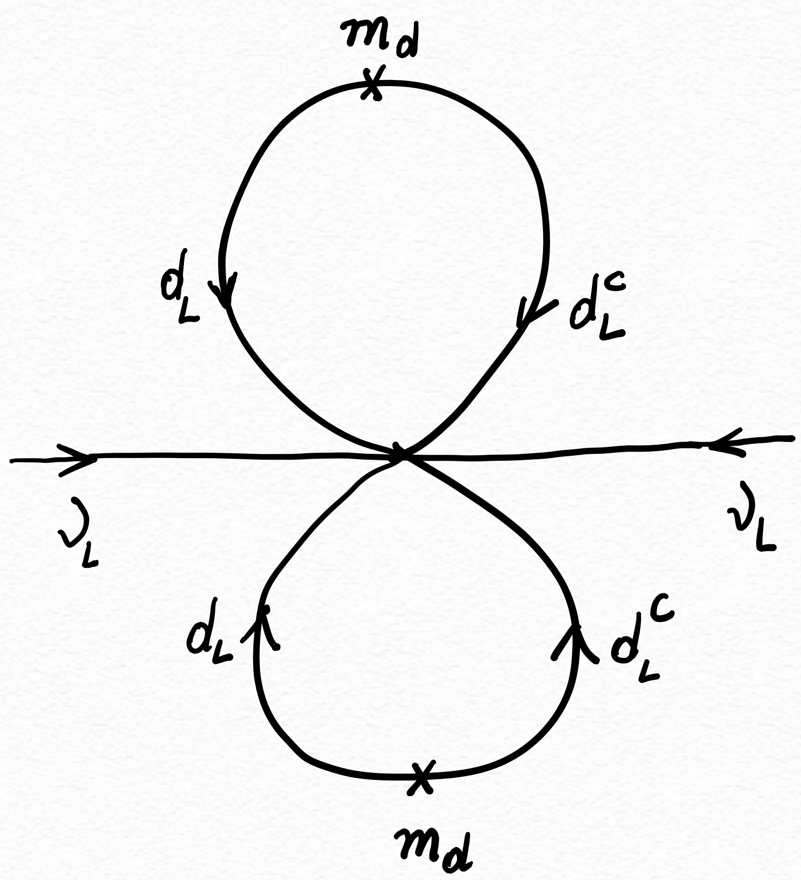
Dvali, GS in progress

$$O = \frac{1}{\Lambda^5}(e_L e_L)(u_L u_L d^c_L d^c_L)$$

typical operator

SU(2) weak

$$O = \frac{1}{\Lambda^5}(\nu_L \nu_L)(d_L d_L d^c_L d^c_L)$$



neutrino mass

$$m_\nu \simeq (\frac{\alpha}{4\pi})^2 \frac{m_d^2}{\Lambda}$$

$$\Lambda \simeq TeV$$

$$m_\nu \simeq 10^{-1}\, eV$$

too close for comfort?

(1)

$$(e_L \; e_L) \times \begin{cases} u_L u_L \; d^c_L d^c_L \\ u_R u_R \; d^c_R d^c_R \end{cases} \qquad (O_1)$$

$\updownarrow$ +

$$(\nu_L \; \nu_L) \times \begin{cases} d_L d_L \; d^c_L d^c_L \\ u_R u_R \; u^c_R u^c_R \end{cases} \qquad (O_2)$$

(1′1′) $(e_L u_L)(e_L d^c_L)(u_R d^c_R) \qquad (O_3)$

SU(2) $\updownarrow$ +

$(\nu_L \; d_L)(\nu_L \; d^c_L)(u_R \; u^c_R)$

$$\Rightarrow \boxed{m_\nu = \left(\frac{\alpha}{\pi}\right)^2 \frac{m_u m_d}{\Lambda}}$$

Generations - Lepton Flavour Violation?

$$O_\mu = \frac{1}{\Lambda^5}(\mu_L \mu_L)(c_L c_L d_L^c d_L^c) \qquad O_e = \frac{1}{\Lambda^5}(e_L e_L)(u_L u_L d_L^c d_L^c)$$

↓ expect

$$\frac{1}{\Lambda^2}(c\,\mu)(\bar{u}\bar{e}) \rightarrow \Gamma(D^0 \to \mu\bar{e}) \simeq \frac{m_D^5}{\Lambda^4} \rightarrow \Lambda \gtrsim 10^5 GeV$$

$0\nu 2\beta$ hopelessly small

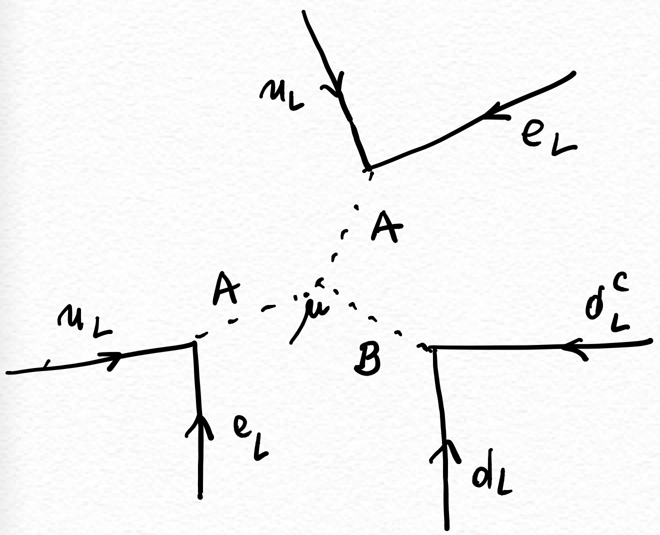
flavour could be conserved → mass suppression can save it

(Poor person's) UV completion

$$\mathcal{L}_{new} = A(u_L e_L + d_L \nu_L) + B\, d_L^c d_L^c + \mu\, A\, A\, B$$

A = scalar leptoquark

B = scalar di-quark



$$\frac{1}{\Lambda^5} = \frac{\mu}{m_A^4\, m_B^2} \qquad m_B \gg m_A \text{ helps}$$

$$m_A \gtrsim 2\, TeV \qquad \frac{\mu}{m_B^2} \gtrsim 10^{-6}\, GeV^{-1}$$

ATLAS 2006.05872

$$m_\nu \simeq \left(\frac{\alpha}{4\pi}\right)^2 \mu \frac{m_d^2}{m_B^2} \simeq 10^{-4}\, eV$$

negligible

Generations - Lepton Flavour Violation?

$$\mathcal{L}_{new} = A(u_L e_L + c_L \mu_L) + B(d^c_L d^c_L + s^c_L s^c_L) + \mu\, A\, A\, B$$

K -Kbar mixing → $m_B \gtrsim 10^6\, GeV$

$\Gamma(D^0 \to \mu \bar{e}) \simeq \frac{m_D^5}{m_A^4}$ → $m_A \gtrsim 10^5\, GeV$

$0\nu 2\beta$ hopelessly small

way out: A, B carry flavour

mass suppression can save it → artificial, but in principle possible

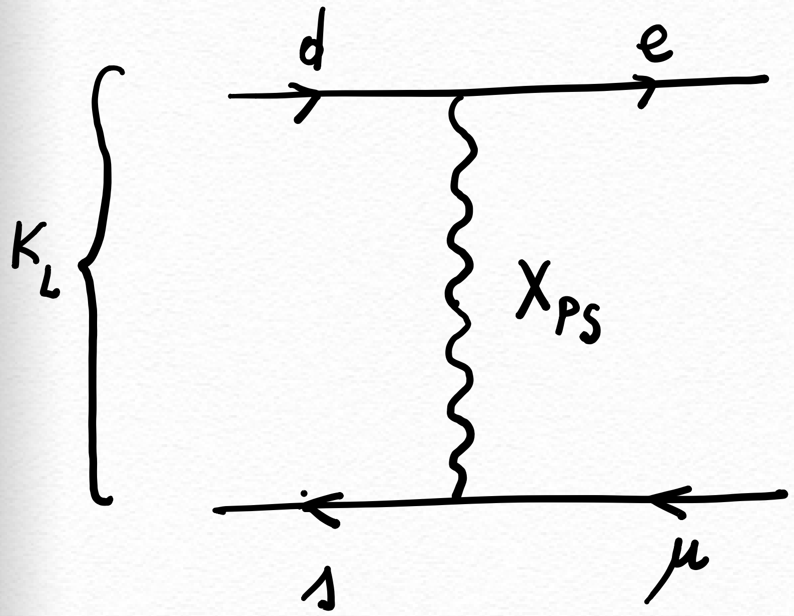
UV completion: theory

quark - lepton unification

Pati - Salam $SU(2) \times SU(2) \times SU(4)$

$$U = \begin{pmatrix} u \\ u \\ u \\ \nu \end{pmatrix} \quad D = \begin{pmatrix} d \\ d \\ d \\ e \end{pmatrix}$$

LFV in gauge boson interactions



$K_L \to \mu \bar{e}$

scale large

$\Lambda \gtrsim 10^5 GeV$

in previous examples
flavour imposed by hand

assume scalar leptoquarks light?

Neutrino mss: Weinberg d=5

Weinberg '79

$$\ell = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

$$O_{\not{L}} = \frac{c_W}{\Lambda} \ell\, \ell\, \Phi\, \Phi$$

UV completion - small Yukawa

$c_W \ll 1$ natural

Φ = SM Higgs

large scale claim ($c_W = 1$) unjustified *Weinberg 'SM50 ...*

no direct physical process → not the right operator

only message: neutrino = Majorana

right operator → $\frac{1}{\Lambda^5}(e\, e\, u\, u\, \bar{d}\, \bar{d})$ 0nu2beta

Measuring parameters

measuring masses, couplings etc - essential

not so much because of a theory of these parameters

rather, to constrain and test a fundamental theory

SM - crucial to measure CKM elements, particle masses - this is how we tested the theory - and this is how we test theories in general

Why disparity of quark and lepton mixing angles?

not a good question a priori:
comparing apples and oranges

relevant in grand unification

example: SO(10) model with type II seesaw

Bajc, GS '2005

small 2-3 quark angle
-> large atmospheric mixing

however, SO(10) scale too close to Planck

SM and gravity

$$\langle \bar{\nu}\nu \rangle = \Lambda^3_{gravity} \lesssim M_P^3 \, exp(-N)$$

N = # of degrees of freedom

Dvali 2017

SM: N = 124 $\Lambda_{gravity} \simeq GeV$ can affect neutrino

Even electron? *Dvali, GS in progress*

LR theory and gravity

$$\Lambda^3_{gravity} \simeq M_P^3 \exp(-N_{dof})$$

LR Model: N = 148

$$\Lambda_{gravity} \simeq MeV$$

can affect predictions?

Leptogenesis $M_{W_R} \gtrsim 30\, TeV$ to get out of equilibrium

plain seesaw = works - but cannot be wrong

LNV violating N decays through MD

$$M_\nu = -M_D^T \frac{1}{M_N} M_D \quad \rightarrow \quad M_D = i\sqrt{M}_N\, O\, \sqrt{M}_\nu$$

O = arbitrary complex orthogonal matrix

LR - O is determined, MD predicted from MN and Mnu

more serious problem: how to test the genesis?

Digression: CP phase and genesis

BBC, NYT…

CP leptonic = probe of genesis

wrong

genesis through MD

$$M_D = i\sqrt{M}_N\, O\,\sqrt{M}_\nu$$

O = arbitrary complex orthogonal matrix

EW genesis similar to SM

Dark matter $m_N \simeq keV$ spectrum and VR fixed

$M_{W_R} \gtrsim 20\,TeV$ or $M_{W_R} \simeq 5\,TeV$

Nemevsek, GS, Zhang ‘2012

Bezrukov, Hettmansperger, Lindner ’2009

Feinberg, Goldhaber '59

example $$\frac{g_{LNV}}{m_e}\pi^+\,\pi^+ e\,e$$

still, use electron mass cutoff - instead Fermi scale

↓

coupling almost vanishing $g_{LNV} \lesssim 10^{-25}$

effective field theory took time

Dvali, GS in progress

SO(10): N ~ 250

MSSM: N ~ 250

$$\Lambda_{gravity} \simeq 10^{-8}\, eV$$

negligible

SO(10) free from gravity - but close to strong coupling scale

MSSM: what to say :(

↓

no free lunch :(

$$\langle T\rangle = v\,\mathrm{diag}(1,-1)$$

↓

$$M_u = M + vY_T, \quad M_d = M - vY_T$$

NFC → M and Y diagonal simultaneously

↓

M_u and M_d simultaneously diagonal

↓

$$V_{CKM} = 1$$